



POST-PROCESSING ADAPTED TO ADDITIVE  
MANUFACTURING

FINAL REPORT

INTRODUCTION TO ADDITIVE MANUFACTURING (ME-413)

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# 1 Introduction

Manufacturing is the cornerstone of technological advancement and a key driver of modern society allowing us to produce everyday items as well as the tools to make them. The process consists of taking raw materials and transform them via energy to obtain the desired product. Traditionally, this can be done via a subtractive model where material is removed from the bulk to give its final shape or as in the replicative model, a shaping tool can be utilized as a means where the material can be added or deformed. In recent times, a third approach known as additive manufacturing (AM) has emerged, that bases its foundations on addition of material but without the requirement of a shaping tool.

Additive manufacturing (AM) enables the production of components by using materials such as wire, powder, or photoresist material as the feedstock. Through various consolidation mechanisms, successive layers generated from the slicing of a 3D CAD model are fused to build the final part [1]. Overall, it can be said that complex geometries can be manufactured in little time with lower cost. The speed is just not a matter of fact of building time but also takes into account the iterative process that is common with the traditional methods as well as the capability to manufacture the products on site as compared to shipping from a specialized traditional manufacturing plant [2]. Which makes this technology shine especially in the case of prototyping, an essential step with every product that reaches the market. Furthermore, some of the geometries might require very specialized equipment to manufacture where some might not even be possible to manufacture at all. Due to these advantages, extensive research is being conducted to advance the underlying technology, optimize process parameters, and tailor them to different materials and consolidation mechanisms. The various AM processes are summarized in figure 1.

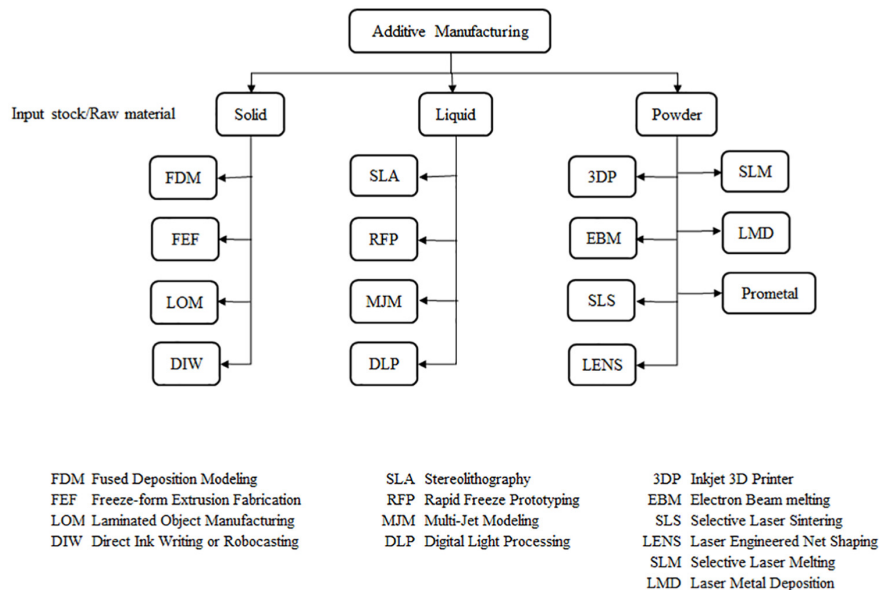


Figure 1: The classification of various AM processes based on the feedstock state [3]

Additive manufacturing unfortunately does not just come with its advantages. Due to

the layer by layer nature of the process, a stairway effect can be seen which shows itself as roughness on the surface. Furthermore, for reasons such as gas entrapment, vaporization or insufficient bonding between the layers internal porosities can also form [4]. Following the scan of the laser path, if always oriented in a certain direction a texture can result in the microstructure which can result in anisotropy in certain properties. Finally each process under AM has its own resolution which regulates the smallest feature or the tolerance in which the part can be produced. In combination with shrinkage and warping, geometrical accuracy is prone to differ from that of CAD drawings. These challenges as well as their significance can be illustrated as in figure 2.

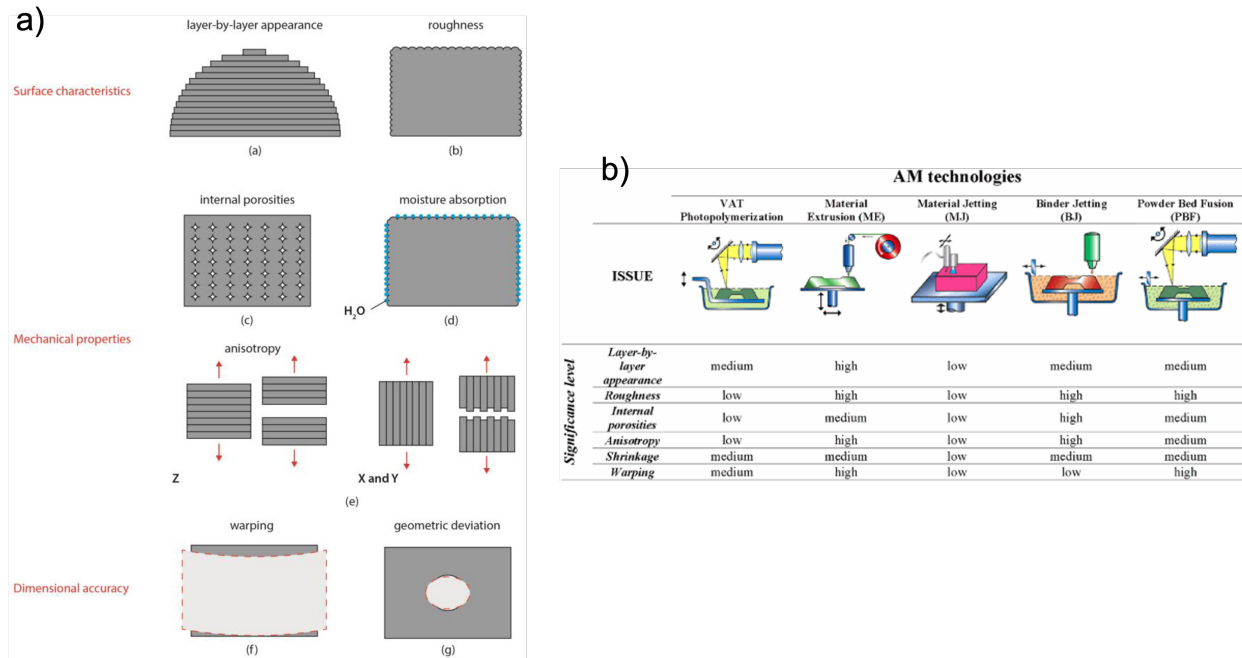


Figure 2: The common defects a) illustrated and b) categorized in significance in relation to production methods [5]

These defects in addition to others such as internal stresses commonly observed in metal AM, dictates the final performance of the part and whether it is applicable to be used in their respective application. For instance the AM of Q/V/W band RF/Microwave hardware is one researched application area of metal AM. For this purpose, it is noted that the geometrical accuracy as well as the roughness of the produced parts dictates whether these additively manufactured parts has the feasibility to be used in this area [6]. Often this is not the case for as built parts, and extra processing steps are necessary. These extra processing steps are defined as post-processing where the aim is to get rid of or minimize any defects that arise in the duration of the manufacturing. The post processing can be categorized as mechanical, chemical and thermal. Some articles also add irradiation as a category however in most of these methods the energy from the laser is used to alter local properties which depending on the intended outcome has been studied under one of the three categories mentioned in this report. In part a of figure 3, the various post processing methods as well as their effect to tackle the main defect groups emphasized for polymer AM has been shown. On

this direction, in part b of the same figure, post-processing methods and their effects on certain properties has been given. It is possible to see the importance of post-processing as much better performance can be obtained and make parts more suitable and safe for their respective use cases.

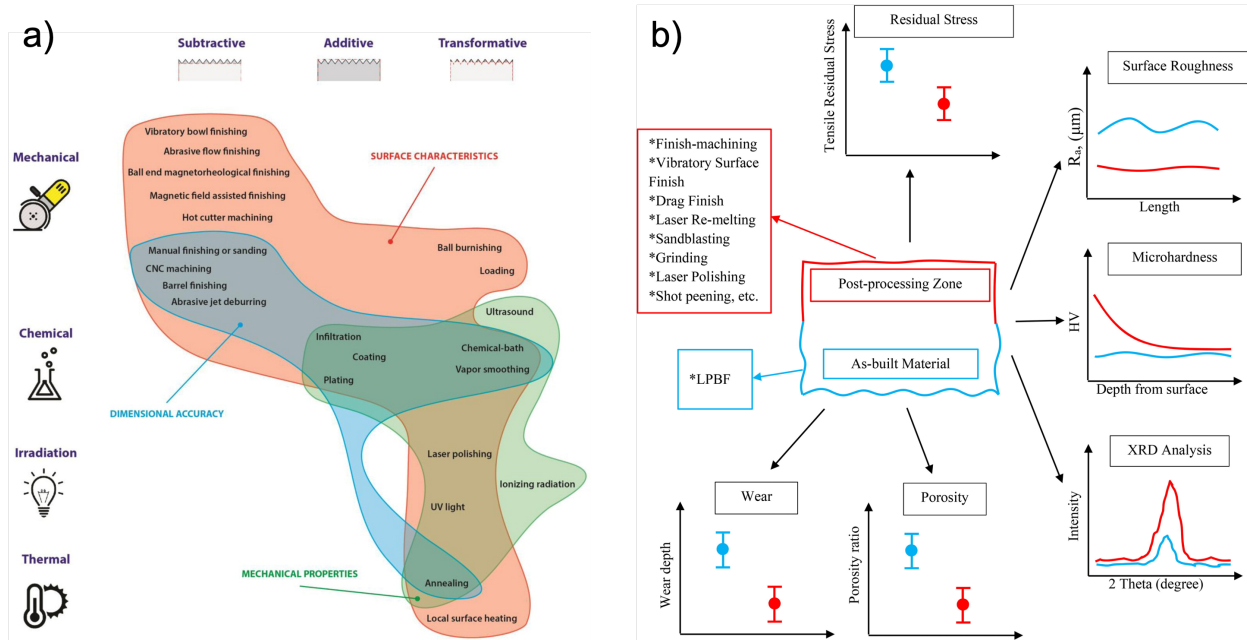


Figure 3: Post processing methods a) highlighting the certain categories as well as the group of defects it aims to tackle mainly on polymer AM [5] and b) emphasizing the improvement of critical properties for mainly metal AM [7]

The post processing starts from the moment the print is finished and also considers steps such as removal of the part from the build plate, depowdering and support removal before other post processing techniques. These steps are also vital however in this report we will mainly focus on treatments that aims to improve a certain property of the part and not focus on processes that is a part of the flow of AM process. Furthermore, it is also common to utilize joining technologies to obtain the final part mostly due to the limited size that can be printed with AM. However, this is a technology of itself containing areas such as welding, brazing, soldering, mechanical joining and adhesive joining. Therefore it will not be in the scope of this report. The aim is to showcase various post-processing treatments categorized under mechanical, chemical and thermal in terms of their mechanism and the resulting increase in properties.

## 2 Mechanical Treatments

### 2.1 Abrasive Methods

#### 2.1.1 Sandpaper polishing

Sandpaper polishing is one of the preliminary postprocessing methods that is applied after Additive Manufacturing. Sandpaper polishing of FDM parts are described by Tiwary et al. [8]. Average surface roughness of the material is decreased from  $14.4 \mu\text{m}$  to  $0.407 \mu\text{m}$ . However, this didn't make the parts to preserve the desired dimensions. From this perspective, manual sandpapering is not well received for the application that necessitates high precision. It decreases the average surface roughness however, also increases the wear and scratches, on the surface.

#### 2.1.2 Fine Abrasive Finishing

Fine Abrasive Finishing (FAF) is a non-conventional post-processing method that utilizes fine abrasive particles suspended in a carrier medium, such as a liquid, paste, or air. In this process, the top surface layer is modified at a microscopic level. The primary objective is not bulk material removal but surface refinement. Surface roughness is reduced by removing micro-peaks and sealing surface pores. The overall aim is to enhance fatigue life and improve wear and corrosion resistance.

A study was conducted by Iquebal et al. [9], who combined traditional machining processes with a non-conventional fine abrasive finishing (FAF) method for final surface treatment. They used Laser Powder Bed Fusion (LPBF) method to manufacture a cylindrical SS316L specimen, as shown in Figure 4a, which exhibited an initial surface roughness of approximately  $S_a \sim 15.76 \mu\text{m}$ .

Afterwards, a flat surface of the cylinder was machined using a milling machine equipped with a 4-flute end mill, as shown in Figure 4b. Following milling, the surface roughness decreased to  $S_a \sim 1.741 \mu\text{m}$ . Subsequently, the surface was pre-polished using a Buehler Metaserv Grinder-Polisher with SiC abrasives of grit size 320. This intermediate step was necessary before the FAF process to remove machining marks and deep scratches.

The FAF process was then applied by polishing the surface with an alumina-based aqueous suspension in multiple cycles. Continuous FAF application can lead to abrasive particle agglomeration, forming larger clusters that may damage the surface. Therefore, after several polishing cycles, the abrasive medium was renewed with a fresh suspension.

At the end of the process (Figure 4c), a final surface roughness of approximately 25 nm was achieved — an exceptionally fine finish for additively manufactured SS316L.

The FAF mechanism improves surface finish and reduces porosity primarily through material redistribution rather than material removal, allowing the process to enhance surface quality without affecting the part's dimensional accuracy [10].

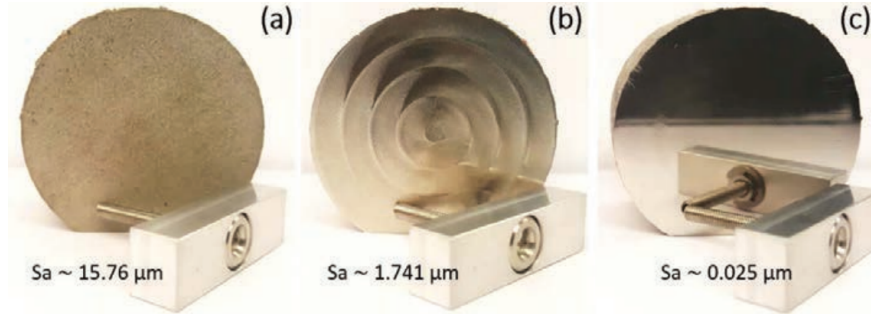


Figure 4: SS-316L Surface topographies: (a) Laser fabricated surface ( $S_a \sim 15.76 \mu\text{m}$ ); (b) after dry milling ( $S_a \sim 1.741 \mu\text{m}$ ); and (c) after fine abrasive finishing (FAF) ( $S_a \sim 0.025 \mu\text{m}$ ). [9]

The images, shown in Figure 5, were captured using a white-light interferometer during different stages of manufacturing: after additive manufacturing (AM), after milling, and after fine abrasive finishing (FAF), sequentially. It can be clearly observed that after the laser powder bed fusion (LPBF) stage, the surface exhibits a predominant granular structure with inter-granular voids. Following the face milling operation, the main surface defects observed are tool marks and chatter-induced deviations. Finally, after the FAF process, the surface quality is significantly improved, showing an almost uniform and smooth finish.

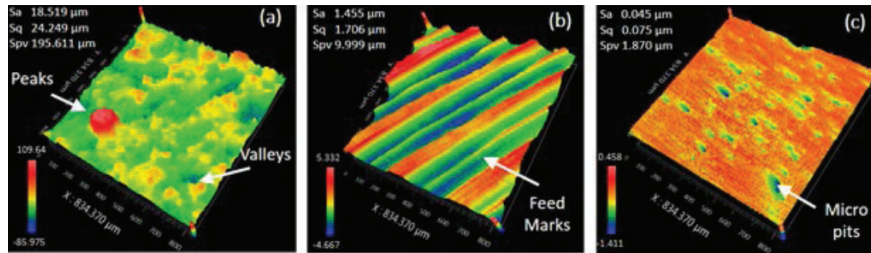


Figure 5: Evolution of the surface morphology: (a) AM surface (b) Milling Surface, and (c) FAF Surface [9]

### 2.1.3 Abrasive Flow Finishing (AFF)

Abrasive Flow Finishing (AFF) is a process that uses a semi-solid material filled with fine abrasive particles. In this process, the abrasive medium is pushed back and forth through or across the workpiece. This motion gently removes tiny surface peaks and smooths out irregularities. The basic principle of the process is illustrated in Figure 6a. These surface irregularities are generally caused by adhesion, agglomeration, or incomplete melting during the additive manufacturing process. Tensile residual stresses on the surface may also develop due to rapid thermal cycles and solidification gradients inherent to metal additive manufacturing. AFF provides a feasible and effective way to finish AM parts, improving both surface quality and mechanical performance.

In the polishing process of Abrasive Flow Machining (AFM), the abrasive medium acts as a flexible tool that continuously deforms and adapts to the shape of the workpiece [11].

This medium is typically composed of a polymer-based carrier mixed with abrasive grits, which remove microscopic amounts of material through scratching and micro-chipping. In the study by Peng et al. [11], the workpiece was additively manufactured using AlSi10Mg aluminum alloy. To better measure the surface erosion, a small hole was drilled, and its bottom was taken as a reference point, as shown in the corresponding Figure 6b. A laser scanning microscope was used to monitor the surface evolution during the finishing process.

It is important to note that a uniform surface finish requires multiple processing cycles. As shown in Figure 6b, the main surface defects—primarily caused by unmelted metal powders and agglomeration—were largely eliminated within the first quarter of the total processing cycles. Beyond this stage, bulk material removal became dominant. Up to about 90 cycles, the major surface defects disappeared, and from 90 to 390 cycles, additional material removal continued to refine the surface.

At the end of the process, the surface roughness ( $S_a$ ) was reduced to approximately  $1.8 \mu\text{m}$ . It is also noteworthy that AFF not only improves surface roughness but also significantly reduces tensile residual stresses, leading to enhanced surface integrity.

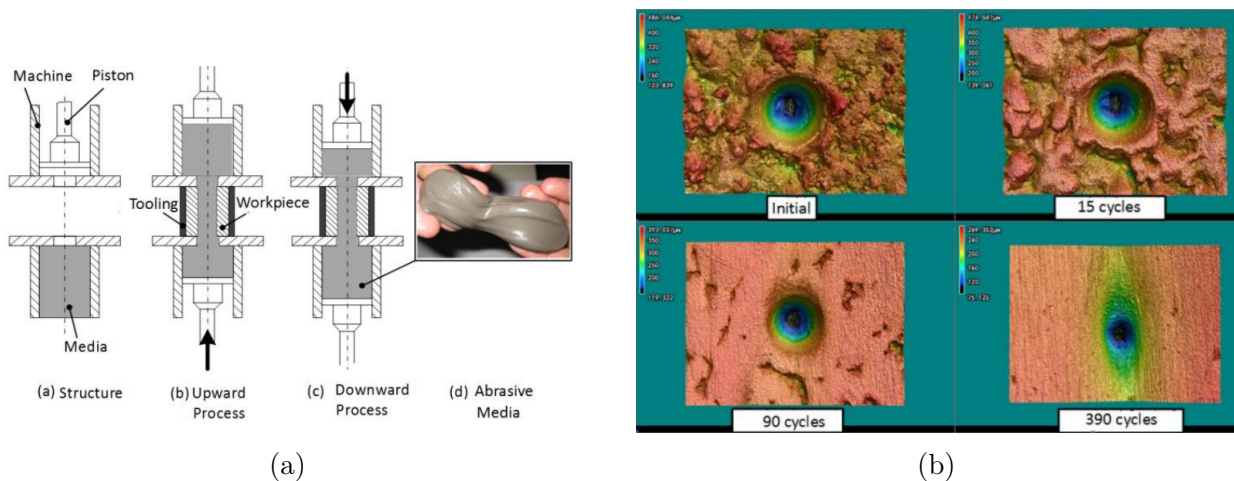


Figure 6: (a) schematic of the abrasive flow machining setup, and (b) surface morphology of the processed part. [11]

### 2.1.4 Abrasive Jetting (AJ)

In the abrasive jetting process, a stream of abrasive particles is directed onto the surface to be finished at a predetermined, non-vertical inclination angle [12]. This inclination angle is an important process parameter. If the jet is completely vertical, the particles collide directly with the surface, causing excessive erosion. Therefore, an oblique angle is preferred. The process can be performed manually or along a predefined automated path using a robotic system. A variety of abrasive materials can be used, such as aluminum oxide, glass beads, and silicon carbide.

Leong et al. [13] investigated the finishing of jewelry patterns produced by stereolithography (SLA). They used two types of abrasive materials: aluminum oxide and glass beads. Three other process parameters were examined — blasting time, blasting distance, and air pressure. The results showed that aluminum oxide performed better as the abrasive medium for SLA-produced parts. Among the process parameters, air pressure and blasting time had the most significant effects on the surface quality, while blasting distance had a relatively minor influence.

Despite its effectiveness, one of the main limitations of the abrasive jetting process is its lack of flexibility when dealing with complex geometries, especially those involving confined or curved surfaces [12].

A closely related technique to abrasive jetting is abrasive jet machining. The key distinction is that abrasive jetting is primarily used as a post-processing or surface-finishing method, whereas abrasive jet machining is mainly employed for material removal operations such as cutting hard and brittle materials or drilling micro-holes [14]. In other words, abrasive jet machining focuses on erosion-based material removal, not on finishing.

## **2.2 Subtractive Machining Methods**

### **2.2.1 Machining**

There is relatively little research on the application of machining processes to additively manufactured (AM) parts. Pandey et al. [15] investigated whether the staircase surface texture characteristic of FDM-printed parts could be smoothed using a conventional mechanical subtractive process — machining with hot cutters. Heating was applied to facilitate material removal, as the elevated temperature softens the polymer during cutting.

The main process parameters studied were cutting speed, surface inclination, and rake angle. The results showed that increasing the cutting speed beyond a critical threshold leads to higher surface roughness. Similarly, increasing the rake angle resulted in rougher surfaces, while the optimal rake angle for FDM parts was found to be  $10^\circ$ .

In addition to these parameters, other factors such as depth of cut and feed rate also influence machining performance. The specific effect of the depth of cut on surface quality was further investigated by Boschetto et al. [16].

## **2.3 Mechanical Deformation-Based Methods**

### **2.3.1 Ultrasonic Nanocrystal Surface Modification (UNSM)**

Ultrasonic Nanocrystal Surface Modification (UNSM) is a mechanical surface treatment technique in which a hardened tip vibrates at an ultrasonic frequency, superimposed on a static load applied to the treated surface. The working principle of the UNSM process is illustrated in Figure 7.

Ma et al. [17] investigated the effect of UNSM on the surface finish of AlSi10Mg alloy fabricated by Direct Metal Laser Sintering (DMLS). In their setup, a tungsten carbide ball was used as the striking tip to scan the surface. During processing, the tool generates high-frequency ultrasonic vibrations (approximately 20 kHz) with an amplitude between 8–20  $\mu\text{m}$ , while a static force of about 10 N is applied. The tool continuously scans the surface, inducing severe plastic deformation in the near-surface layer. As a result, the surface roughness decreases significantly — in their experiments, the  $R_a$  value was reduced from 18  $\mu\text{m}$  to 3.5  $\mu\text{m}$  using an 8  $\mu\text{m}$  vibration amplitude.

Additionally, the UNSM process reduces tensile residual stresses and enhances fatigue resistance of the treated material. The height difference between surface peaks and valleys, initially reaching up to 100  $\mu\text{m}$  in the DMLS-fabricated part, was reduced to below 15  $\mu\text{m}$  after UNSM treatment. Furthermore, a significant reduction in surface porosity was also observed.

The main process parameters are determined to be the static load, dynamic load, interval between adjacent scan lines, and the scanning speed.

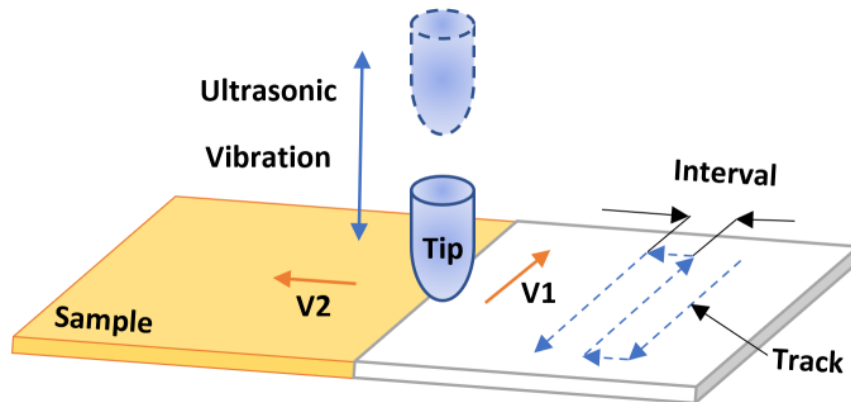


Figure 7: Schematic of the UNSM process [12]

### 2.3.2 Cavitation Abrasive Finishing (UCAF)

Cavitation is a major challenge in propeller systems, as it damages propeller blades. This occurs when low-pressure regions in water cause local boiling and the formation of vapor bubbles. When these bubbles collapse due to the surrounding high pressure and surface tension, they generate intense micro-jets and shock waves that impact nearby surfaces. While cavitation is considered a serious problem in the naval industry, the same mechanism can be utilized beneficially for surface finishing. Ultrasonic Cavitation Abrasive Finishing (UCAF) employs controlled cavitation to improve surface quality and reduce roughness. In this process, the surface is subjected to harmonic cavitation shocks, which progressively modify its microtopography.

Tan et al. [18] implemented the UCAF method on specimens fabricated by Direct Metal

Laser Sintering (DMLS) using Inconel 625. This material, known for its excellent heat and corrosion resistance, is widely used in the aerospace industry. The experimental setup involved a high-power ultrasonic generator operating at a frequency of 20 kHz, with vibration amplitudes of  $60\ \mu\text{m}$  and a horn tip diameter of 12.7 mm. The specimen was immersed in a liquid medium using a fixture, while the horn tip was positioned approximately 0.8 mm above the specimen to prevent direct contact between the horn, specimen, and abrasive particles. The schematic representation of the UCAF mechanism is shown in Figure 8.

It is important to note that the experiments were conducted under two conditions: (1) using cavitation alone, and (2) using cavitation combined with abrasive particles. The abrasive materials had grit sizes of 400, 800, and 1200, with a concentration of 5 wt%.

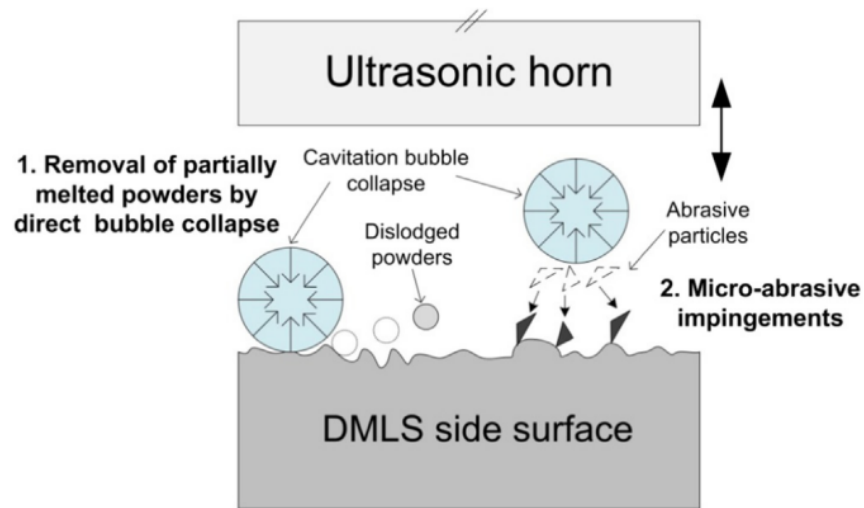


Figure 8: UCAF mechanism [18].

The DMLS-produced Inconel 625 surfaces exhibited three main types of irregularities [18]:

- Almost spherical particles ( $10\text{--}55\ \mu\text{m}$ ), corresponding to partially melted powders.
- Irregularly shaped surface peaks ( $> 60\ \mu\text{m}$ ), caused by the agglomeration of several partially melted powders or by the balling phenomenon.
- Small “step” discontinuities between neighboring layers.

During UCAF processing, cavitation bubbles tend to form around surface peaks. Upon collapsing, they erode these peaks, leading to a reduction in surface roughness. Specifically, spherical particles smaller than  $60\ \mu\text{m}$  were effectively removed regardless of whether micro-abrasives were added. However, when micro-abrasive particles were present in the medium, the shock waves generated by cavitation accelerated these particles, resulting in additional micro-cutting effects. This was confirmed by the presence of fine cutting marks observed on the treated surfaces. Consequently, the removal of surface irregularities was significantly

enhanced when abrasive particles were included.

Surface roughness measurements were obtained using a profilometer and Scanning Electron Microscopy (SEM). The results showed that the initial surface roughness of approximately  $6.5\text{--}7.5\ \mu\text{m}$  ( $R_a$ ) was reduced to about  $2.65\ \mu\text{m}$  after applying the combined cavitation and micro-abrasive process.

## 2.4 Mass Finishing

Mass finishing is defined as a group of post-processing methods in which multiple metallic or non-metallic components are simultaneously subjected to abrasive surface finishing operations to achieve surface refinement, geometry modification, and surface cleaning and preparation [19]. While standard post-processing techniques such as grinding and lishing encounter significant difficulties when applied to AM parts with relatively complex geometries that include internal features in addition to external surfaces, mass finishing can serve as a more suitable alternative [20]. Additionally, since multiple parts can be processed simultaneously, mass finishing can serve as a cost-effective post-processing method. As reported by Fan et al. [21], the surface finishing cost per part in mass finishing can be reduced by nearly half compared to sand blasting, depending on the batch size, while maintaining a consistent surface quality among all processed parts. Although mass finishing (MF) offers several advantages, as stated by Fan et al. [22] its surface improvement mechanism is highly complex. The interactions between the media and the workpiece can vary considerably even within the same process. These interactions and the resulting surface characteristics are influenced by factors such as media geometry, loading ratio, lubricant flow rate, and the physical properties of the workpiece. Mass finishing processes are divided into several types based on bowl movement and media–surface interaction: vibratory surface finishing (VSF), stream finishing, rotary barrel finishing, centrifugal barrel finishing, centrifugal disc mass finishing, cascade finishing, and drag finishing [23]. Before discussing the details of these various mass finishing techniques, some fundamental concepts and mechanisms should be explained in order to enhance the understanding of these methods.

### 2.4.1 Abrasive Media

Media in mass finishing processes is defined as a loose or free-flowing abrasive material contained within a chamber or container. When this media is energized through various methods, it moves and comes into contact with the workpiece surfaces, enabling mechanical interaction with the workpiece to remove surface irregularities [19]. In selecting abrasive media, the geometry, material, and strength of the workpiece must be considered to determine the appropriate shape, size, material, and weight of the abrasive particles .

- Shape and Size Selection

The shape selection of abrasive media plays a critical role in mass finishing processes. Fig. 9 illustrates several abrasive media shapes, including the most common types such as cylindrical, spherical, pyramidal, and sharp-edged star forms [23].

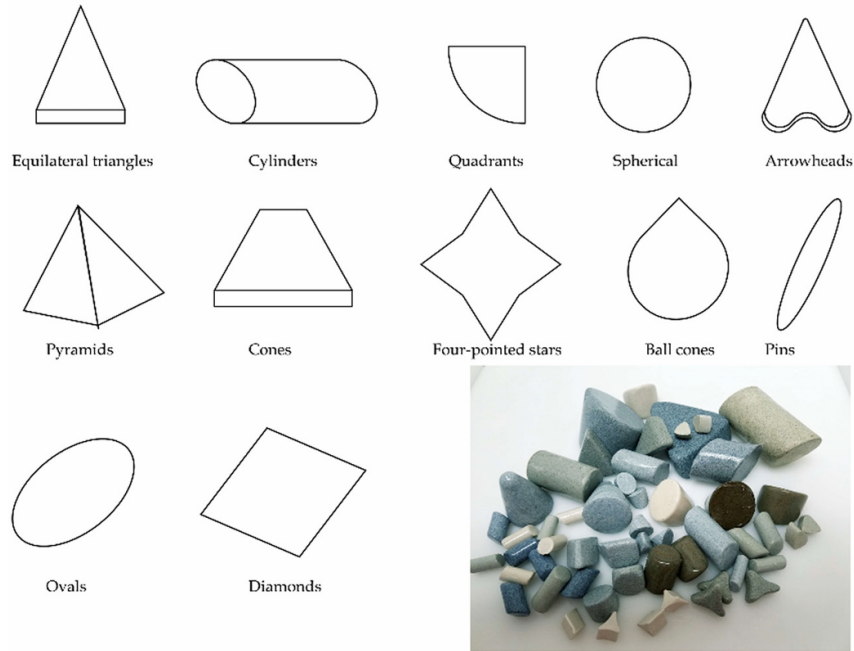
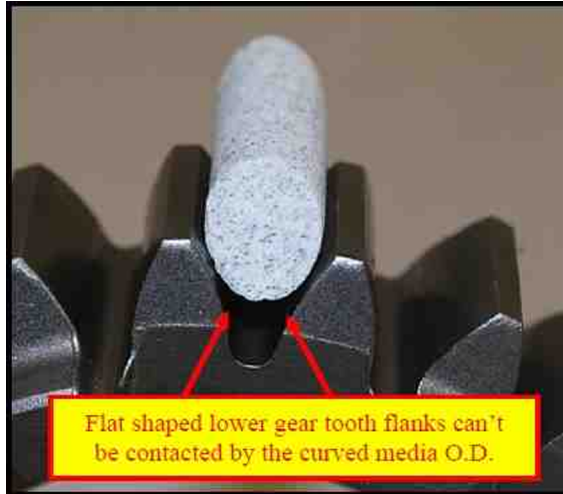


Figure 9: Some common types of vibrating finishing media [23].

Among the possible contact patterns between the media and the workpiece—planar, linear, and point—planar contact is the most efficient due to its maximum surface-to-surface interaction. However, when determining the appropriate abrasive media shape and size, it is essential to consider the geometry of the workpiece, particularly to ensure effective contact in recessed, confined, or narrow regions while minimizing the possibility of media lodging within internal or tight areas of the part. As shown in Figure 10, the shape of the abrasive media influences the contact efficiency on gear tooth surfaces; the cylindrical media provides limited contact, while the ellipse-shaped media ensures better interaction with the lower tooth flanks. In addition, it has been stated that abrasive media also undergoes wear and volumetric mass loss over time, which can negatively affect the final surface quality and required processing time [24]. In a study conducted on additively manufactured 316L stainless steel samples, it was observed that larger media size, due to its higher mass, punching effect, and inertia, resulted in improved surface quality and higher material removal rate [25].



(a) A poor media shape choice.



(b) Enhanced media shape choice.

Figure 10: Comparison of abrasive media shape choices [24].

- Material & Composition

Five main material types are used for loose abrasive media, including ceramic, plastic and synthetic, metal, precision, and micro-bite [20]. In mass finishing, abrasives such as aluminum oxide, silica, and silicon carbide are embedded within the media matrix during manufacturing through mixing and curing (for plastic media) or sintering (for ceramic media) [26]. These abrasive particles are gradually exposed as the media wears, enabling consistent cutting and surface finishing performance. Ceramic media are typically used for aggressive material removal and durability, especially for hard metals such as steel or titanium alloys, while plastic or synthetic media are preferred for fine finishing, deburring, or polishing of softer materials like aluminum or brass due to their lower density and gentler action. Among these media types, ceramic media have been widely studied due to their broad industrial use. Uhlmann et al. [26] demonstrated that different ceramic media compositions cause significant variations in material removal rate and surface quality. Even the non-abrasive ceramic medium (RF) reduced surface roughness by about 22.7%, confirming the mechanical effect of the binder phase. According to their findings, media with higher abrasive content achieved greater improvement within the same processing time, while the limiting roughness tended to be slightly higher, although not significantly distinctive across the tested media.

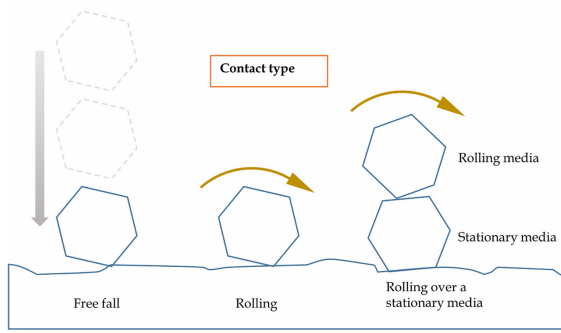
#### 2.4.2 Compound

In mass finishing operations, compounds are typically introduced as both lubricating and cleaning agents, supporting smooth media–workpiece interaction. Certain compounds are

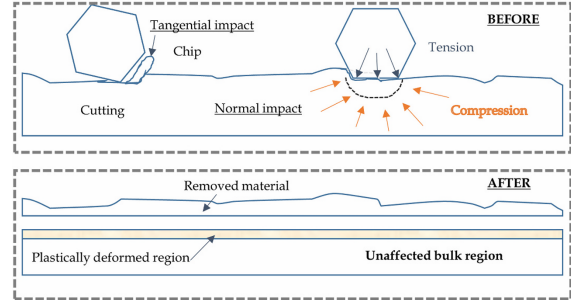
chemically active and can enhance the material removal process by accelerating surface reactions. Increasing the level of lubrication encourages the media to slide over the surface rather than to generate direct normal impacts. This shift reduces the ratio of normal to tangential impulses, thereby limiting the plastic deformation per impact and consequently resulting in lower surface hardness. Improved lubrication also leads to a lower friction coefficient, which minimizes pitting and surface damage, producing a finer polished finish [27]. Moreover, the presence of lubrication helps prevent ceramic wear debris from embedding into the workpiece surface, thus achieving smaller surface roughness values (Ra) [28]. However, excessive use of compound can dampen media motion, reducing the vibratory intensity and overall process efficiency. Experimental observations further reveal that, under dry (unlubricated) conditions, media impacts occur primarily in the normal direction, whereas tangential sliding dominates under wet (lubricated) conditions. Consequently, the dry process exhibits a peening-type effect, while the wet condition favors a polishing behavior. In addition, more media debris tends to adhere or become embedded on the surface after dry finishing, whereas in the wet condition, the washing action of the lubricant effectively removes such residues [28]. Therefore, lubrication in mass finishing is primarily governed by the compound composition and its concentration in the process solution, meaning that the balance between chemical reactivity, cleaning capability, and viscosity directly determines the surface quality and process efficiency.

### 2.4.3 Mechanism

According to the article [29], the particle–surface interaction in the vibratory surface finishing (VSF) process can occur in three distinct modes: free-fall, rolling, and stationary media impacted by surrounding particles. During the free-fall mode, media pellets strike the workpiece surface at various angles, generating both normal and tangential impacts. The normal impacts induce plastic deformation of the surface, whereas the tangential impacts contribute to material removal and surface abrasion. In the rolling mode, media pellets move across the workpiece surface, leading to a mixed effect of normal and tangential impacts. This interaction produces numerous small craters and minor impact peaks, where the magnitude of the forces depends on the inclination of the workpiece surface. In the third mode, a stationary media pellet remains on the surface while being repeatedly impacted by other rolling or falling pellets. This results in a single large crater with a longer-lasting impact force compared to the other two modes and is considered the most common interaction in the VSF process. At this stage, extensive erosion and breaking of partially attached powder particles occur, followed by pore filling, which ultimately improves the surface smoothness and uniformity.



(a) Different types of media-surface contact.



(b) Normal and tangential impact mechanism between media and workpiece.

Figure 11: Vibratory Surface Finishing Mechanism [23].

The general definitions and mechanisms, as well as the concepts of media and compounds, are common to the various mass finishing processes. The various mass finishing techniques described below are built upon this fundamental understanding of the general mechanisms, media, and compounds.

#### 2.4.4 Types

- Vibratory Surface Finishing (VSF)

In this process, the container is vibrated by an unbalanced mass drive system consisting of a motor with eccentric weights that generate cyclical vibrations. This motion causes the media to move in a complex flow pattern and repeatedly impact the workpiece surface. Among the various mass finishing methods, VSF is the most widely used due to its high flexibility, process efficiency, and capability to finish components with complex geometries simultaneously [30].

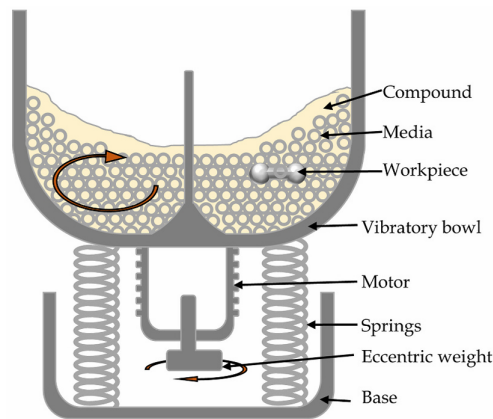


Figure 12: Vibratory Surface Finishing [23].

- Stream Finishing

In this process, a cylindrical bowl filled with abrasive media rotates around its principal axis at high speeds, while the workpiece is held stationary by an independently controlled fixture

and immersed into the rotating media flow. The media particles slide past the workpiece surface in a dominant direction, generating normal contact pressure and high sliding velocity. These interactions lead to intensive material removal, surface smoothing, and the induction of compressive residual stresses [31]. Owing to the high media sliding velocity, the material removal rate in Stream Finishing is approximately one order of magnitude higher than in vibratory finishing [32]. Stream finishing, also referred to as centrifugal or gyro finishing

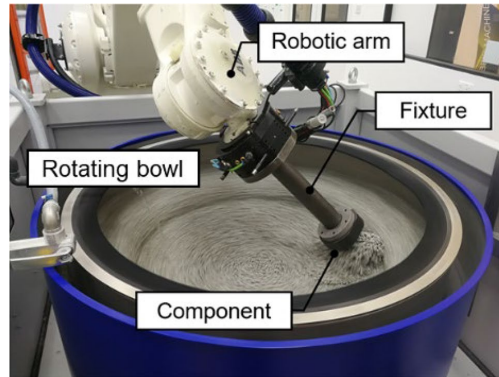


Figure 13: Stream Finishing [31].

- Rotary Barrel Finishing

Rotary Barrel Finishing (RBF) is a process that uses a horizontally oriented container in which multiple workpieces are tumbled together with freely moving abrasive media. As the container rotates around its main axis, the motion propels the media at high speed, generating sufficient pressure and friction on the workpiece surfaces. This continuous circular movement enables uniform, large-scale finishing of all workpieces within the barrel [23].

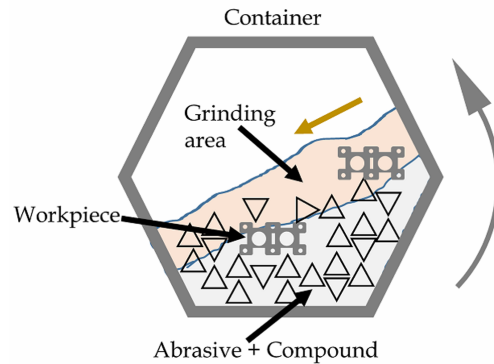


Figure 14: Rotary Barrel Finishing [23].

- Centrifugal Barrel Finishing

Centrifugal Barrel Finishing (CBF) consists of multiple barrels that both rotate and revolve around a central axis at high speed. This dual motion produces strong centrifugal forces, which push the workpieces away from the container walls. Consequently, the workpieces

positioned near the center are subjected to the highest forces, leading to significantly greater finishing efficiency and productivity compared to RBF.

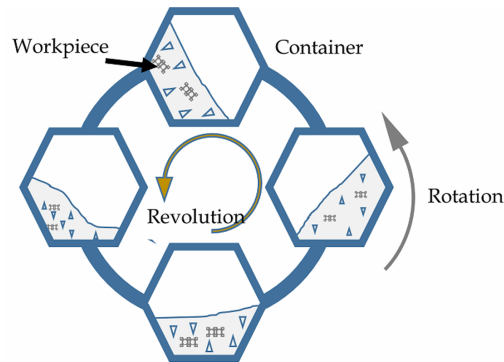


Figure 15: Centrifugal Barrel Finishing [23].

- Centrifugal Disc Finishing

In this process, the workpiece is positioned inside an open drum filled with polishing granules, while a movable base plate generates a toroidal flow of media. The Centrifugal Disc Finishing (CDF) method enables intense contact between the media and the workpiece surface, making it up to twenty times more efficient than conventional vibratory finishing. It is particularly effective for deburring and edge rounding of complex or detailed components.

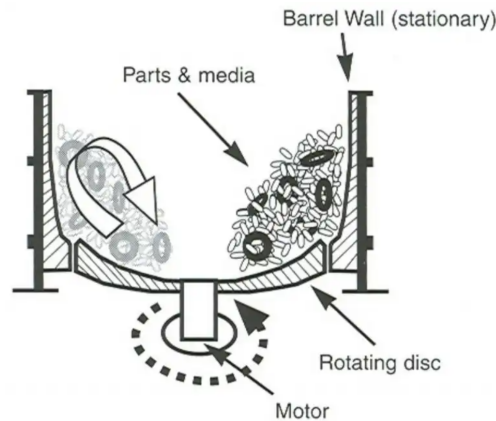


Figure 16: Centrifugal Disc Finishing [33].

- Drag Finishing

After the workpiece is fixed in special holders, it is immersed in a container filled with abrasive media and moved within the media by the motion of the holder. As a result of this contact, high contact pressure is generated on the workpiece surface, enabling high-precision surface quality to be achieved in a short time.

## 2.5 Fatigue Life Enhancement Processes

Most engineering components fail due to fatigue, which occurs under repeated loading at stress levels below the material’s nominal strength. Fatigue failure progresses in two stages: microcrack initiation and crack propagation, eventually leading to fracture. Additive manufacturing (AM) requires special fatigue considerations due to its unique processing conditions that create anisotropic microstructures and rapid solidification effects. Three major AM-related factors reduce fatigue strength. First, surface roughness decreases fatigue performance because features such as the staircase effect, balling, and incomplete melting create numerous crack initiation sites. Second, internal porosity and voids, which result from gas entrapment or insufficient fusion, act as internal defects that significantly weaken the material under cyclic loading. Third, tensile residual stresses form due to thermal gradients during layer-by-layer fabrication, promoting crack initiation and growth. Since current AM technology cannot completely eliminate these issues through process parameter optimization alone, post-processing is necessary to improve fatigue performance. These methods focus on surface enhancement, defect reduction, and introducing compressive residual stresses. [34]

### 2.5.1 Burnishing

The burnishing process is a cold forming operation in which no material removal takes place. Its main purpose is not only to eliminate surface roughness through plastic deformation, but also to enhance properties such as hardness, wear resistance, residual compressive stresses, and fatigue life of the part. The microscopic surface asperities (peaks) are plastically deformed under the applied pressure and the movement of the indenter, flowing into the surface valleys and thereby producing a smoother, brighter, and harder surface. The indenter, which comes into direct contact with the workpiece, can be roller-type or ball-type, and its materials are generally alumina, carbide ceramics, cemented carbide, silicon nitride ceramics, silicon carbide ceramics, and bearing steels. Roller indenters have several advantages, such as being easy to manufacture, allowing for simple adjustment of the applied force, providing a larger contact area, and thus enabling a higher feed rate. However, compared to ball indenters, roller indenters are less adaptable to complex geometries of parts. Moreover, ball indenters can achieve better efficiency under the same applied force. [23]

Chueca de Bruijn et al. [35] investigated the ball burnishing process as a post-processing technique for parts produced by the Fused Filament Fabrication method, which typically exhibit surface roughness due to the stair-stepping effect. Their study demonstrated that ball burnishing significantly reduced surface roughness and led to an increase in both impact energy absorption capacity and fatigue life of the parts. Among the investigated parameters, the applied force and the number of tool passes were identified as the most influential factors affecting the process performance. Furthermore, as showed in fig. 17 the parts printed in the orientation perpendicular to the burnishing direction achieved better surface quality, although no significant improvement was observed in fatigue life for this configuration.

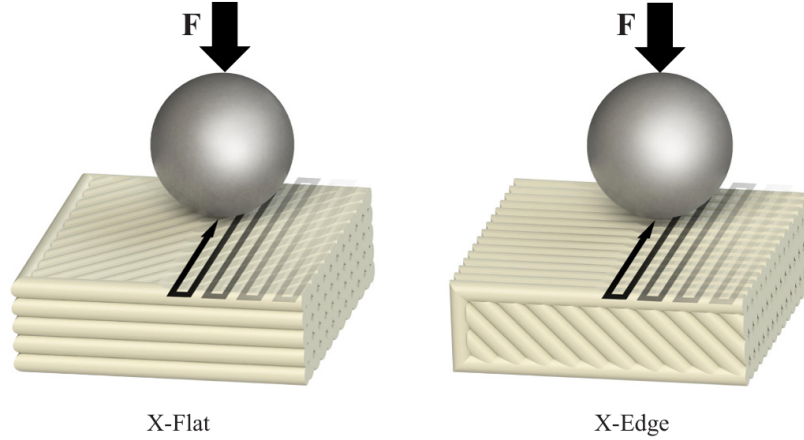


Figure 17: Schematic of the ball-burnishing process showing the burnishing strategy used for each type of FFF sample: X-Flat and X-Edge. [35].

The conventional ball burnishing (BB) process has been further developed into a more advanced variant known as Ultrasonic Vibration-Assisted Ball Burnishing (UVABB). In this enhanced process, an additional vibratory ultrasonic oscillation is superimposed on the conventional linear forward motion of the burnishing tool. This results in a reciprocating motion of the tool in the feed direction, which improves the dynamic contact between the tool and the surface. It is important to note that the main difference between vibratory ball burnishing and ultrasonic ball burnishing lies in their vibration frequency. While conventional vibratory burnishing typically operates within the 20–50 Hz frequency range, ultrasonic-assisted burnishing utilizes much higher frequencies in the kilohertz (kHz) range. This high-frequency excitation significantly enhances the plastic deformation behavior of the surface layer, leading to finer surface finishes and improved mechanical properties [23]. Ultrasonic-Assisted Ball Burnishing (UABB) is a highly effective post-processing technique for improving the surface quality and hardness of various metallic components produced by Additive Manufacturing (AM) [36].

### 2.5.2 Shot Peening

In this post processing technique; small, hard and generally spherical particles are propelled at high velocity toward the surface. Upon impact, these particles transfer kinetic energy to the surface, causing localized plastic deformation. The plastically stretched surface attempts to expand laterally, but this expansion is constrained by the underlying material mass. As a result, work hardening occurs and compressive residual stresses (CRS) develop at and near the surface. Almen intensity is one of the most important indicators of the shot peening process and is related to the characteristics of the shot media type, mass, size, velocity, and hardness. Higher Almen intensity generally results in greater plastic deformation and compressive residual stress. Additionally, because AM parts typically have higher surface hardness than the conventional options, the hardness of the shot media must be carefully selected to achieve the desired effect[23].

### 2.5.3 Laser Shock Peening

Laser shock peening creates compressive stresses by sending strong shock waves into the material with short, powerful laser pulses. When the laser hits the surface, it produces a layer of high pressure plasma. A clear layer on top, often water, keeps this plasma from spreading outward. Because it is confined, the pressure is directed down into the material, forming a strong mechanical impact. This shockwave produces localized plastic deformation at a much deeper depth compared with conventional SP, resulting in deeper and higher magnitude compressive residual stresses. Moreover, LSP causes minimal surface roughening and less strain hardening, making the induced stresses more stable. Although LSP equipment and operation are significantly more expensive, it provides superior fatigue improvement [23].

Hackel et al. [37] studied how laser peening and shot peening can enhance the fatigue resistance of additively manufactured 316L stainless steel samples. Their results showed that laser peening, due to its ability to induce compressive residual stresses much deeper, provides the most significant improvement in fatigue life. Figure 18 illustrates the laser peened, shot peened, and as-built samples they used in their study.

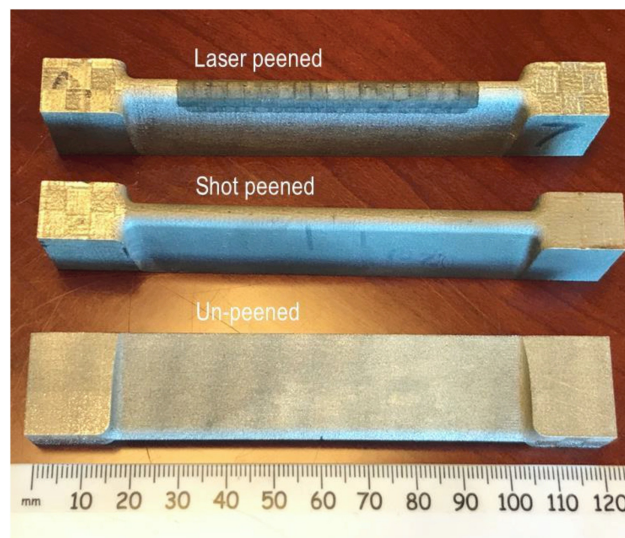


Figure 18: Laser peened, shot peened, and as-built samples [37]

### 3 Thermal Treatments

Thermal post-processing treatments are an important step in additive manufacturing especially for metallic and for certain polymeric parts. They are chosen to reduce residual stresses, homogenize microstructures, and enhance mechanical properties. These methods include high temperature and the parameter such as temperature and pressure depends on the materials and the expected properties at the end. The temperature of heating and cooling as well as the rate will influence the microstructure, the duration needs to be long enough to ensure that the part reached the equilibrium and so a uniform microstructure. A controlled atmosphere can be useful to avoid unwanted reaction. These heat-treatment will be presented in this chapter. [38]

#### 3.1 Hot Isostatic Pressing (HIP)

Hot isostatic pressing is used after sintering to densify the pre-consolidated powder. A typical HIP equipment can be seen in Figure 19. During the process, the part is enclosed within a high-pressure chamber in a controlled atmosphere (usually made of an inert gas) and the temperature is set between the solvus temperature and the melting point (generally between 1000°C and 2000°C and the pressure up to 200MPa).[39]

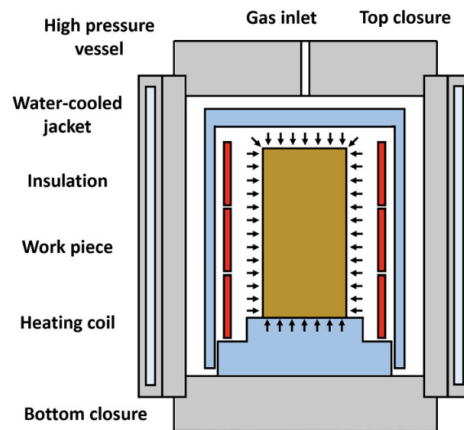


Figure 19: HIP process

Under these high temperature and pressure, the part will undergo plastic deformation and densification, hence a reduction of porosity and voids until 0.01%. This is mainly used for metallic and ceramic part. [38]

At first, it has been developed to consolidate parts but nowadays it is mainly used to increase the density of metallic and ceramic powders. This treatment does not change grain structure and neither the columnar grain. However, it improves the overall mechanical properties by increasing strength, ductility and plasticity. It also reduces the chemical segregation and homogeneity of the microstructure. Benedetti, Toressani and al. increased the fatigue of a part from 221 cycles to 369 cycles and so an improvement of 170% [40]

## 3.2 Sintering and filtering

Another method to consolidate a part is sintering and filtering. These heat treatments are increasing the density of a green body (a compact powder body) to a solid with the desired microstructure. [41]

In sintering, the particle coalescence without liquefaction of them is possible thanks to the controlled heating done below the melting temperature of the main component. If HIP is combined to this process, the process is enhanced. The driving force during the densification is the reduction of surface area. There is some mass transportation mechanism such as surface diffusion, lattice diffusion, vapor transportation and grain-boundary diffusion. The final microstructure needs to be controlled to prevent excessive grain coarsening, which is strongly influenced by the initial particle size, surface condition, grain-boundary characteristic and packing density before sintering. The density can be increase up to 99%. [42]

During filtration, the pores in the part is filled with a liquid metal or alloy that has a lower melting point. The capillary forces allow the liquid to spread into interconnected pores and fills the entire volume. The driven force in this method is also the reduction of surface energy and the infiltration is easier if the wetting angle is low between the material and the liquid and if there is a pressure gradient. [43]

However it is complicated to adjust the final microstructure with HIP, sintering or infiltration. Therefore a traditional heat treatment is needed to reduce internal stresses, improve ductility and fatigue resistance.

It is also possible to do it on polymer parts, as seen in Figure 20, the part is immersed inside low-viscosity thermoset liquid where with the help of vacuum the resin is allowed to diffuse inside the material. Once the pores are filled, a curing step is realized for crosslinking and therefore, strengthening of these once void regions.

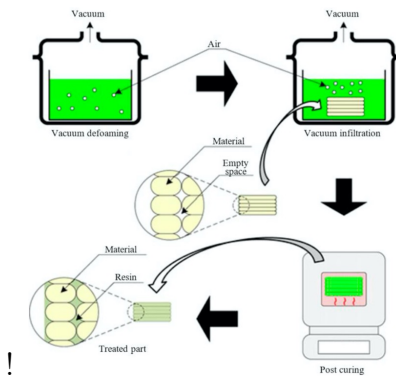


Figure 20: Infiltration [5].

Impens and Urbanic in their study tried the effect of epoxy, cyanoacrylate and polyurethane as infiltrates to study their effect on tensile and compressive strength of the component [44]. It was shown that with respect to a control sample, each case resulted in enhanced mechanical properties.

### 3.3 Annealing

One of the most common thermal post-processing method for metallic part is annealing. The parts are heated and cooled to reduce internal stress and improve their toughness and ductility.

The method is heating up and maintaining a part at a specific temperature and then cooling it. The heating and cooling rates are important and need to be controlled because it will impact the final properties. For steels and Fe-based alloys, normalizing (heating above the upper critical temperature followed by air cooling) refines grain size and produces a uniform ferrite–pearlite or bainitic structure. It is useful for parts that have heterogeneous microstructures with columnar grains or chemical segregation. [45]

After quenching or a martensitic transformation, a tempering can be done to decrease brittleness by controlling precipitation of carbides and a reduction of internal stresses. For tool steels fabricated by laser powder bed fusion, tempering after quenching increases toughness and fatigue resistance while maintaining the hardness. Several tempering cycles are sometimes required to achieve consistent microstructural stability. [45]

Annealing steels and titanium alloys below the recrystallization temperature increase stress relief and sub-grain coarsening without changing the phase composition, it also improve ductility while maintaining the strength. [45]

At higher temperatures, full recrystallization can occur, leading to the formation of equiaxed grains and elimination of cellular or columnar textures. This transformation homogenizes the microstructure and reduces anisotropy, excessive grain growth but dislocation annihilation may decrease yield strength and hardness. For example, in SLM-fabricated Ti-6Al-4V, annealing around 700–800°C transforms the brittle  $\alpha'$ -martensite to a more ductile  $\alpha + \beta$  structure and so it shows a better elongation but a reduced ultimate tensile strength. Similarly, in stainless steels and nickel superalloys, annealing create segregation of alloying elements such as Cr, Mo, and Nb at grain boundaries and stabilize corrosion behavior.[45]

### 3.4 Solution treatment and aging

Hardenable alloys can be precipitated such as AlSi10Mg, maraging steels, and Ni-based superalloys. They require a combination of solution treatment and aging to have an optimal strength. Solutionizing dissolves segregated solute atoms and homogenizes the alloy matrix, typically around the solvus temperature (between 520–540°C for AlSi10Mg; 980–1050°C for Inconel 718). Rapid quenching keed a supersaturated solid solution, and subsequent aging (between 150–180°C for Al alloys or 480–550°C for Ni- and Fe-based alloys) precipitates nanoscale strengthening phases such as  $Ni_3(Ti, Al)$ ,  $\beta' - Mg_2Si$ , or Cu-rich clusters. [45]

For AM components, STA adjust mechanical properties more effectively than annealing alone. Studies report significant increases in yield strength and hardness up to 30–40% while maintaining or slightly reducing ductility. However, improper thermal cycles can cause over-aging, coarsening of precipitates, and decreased toughness.[45]

### 3.5 Stress-relief heat treatment (SRHT)

Methods at low temperature such as stress-relief treatments can be performed (for steels, typically 550–700°C; for Ti-alloys, 600–750°C) to reduce residual stresses without changing the microstructure. These stresses are coming from steep thermal gradients and repeated melting/solidification cycles from the additive manufacturing process. SRHT decreases distortion and cracking, and so increase dimensional stability and improved machinability. [46]

The mechanism create localized plastic relaxation and rearrangement of dislocation networks. For nickel-based superalloys (such as Inconel 718) and precipitation-hardened steels (for example 17-4 PH), stress-relief treatment prior to solutionizing and aging helps prevent crack initiation during high-temperature stages. [46]

The mechanism creates localized plastic relaxation and rearrangement of dislocations. For nickel-based superalloys and precipitation-hardened steels, stress-relief treatment prior to solutionizing and aging helps prevent crack initiation during subsequent high-temperature stages. Kumar and al. proved it can increase average hardness of 23.03

### 3.6 Thermal debinding

Thermal debinding is the first post-processing step for parts made from binder jetting (BJT), material extrusion (MEX), or fused filament fabrication (FFF) using metal or ceramic. The main goal of this process is to remove the organic binder or polymeric additives used to shape and hold the powder particles together during printing but still maintaining the structural integrity of the porous “brown part” prior to sintering. This is achieved by controlled heating in an inert atmosphere (argon or nitrogen), reducing (hydrogen), or vacuum conditions to prevent oxidation and other unwanted reactions. The temperature profile is composed of isothermal plateaus to gradually decompose the binder components and increase their diffusion and evaporation through interconnected pore channels. A slow heating rate is essential because too rapid heating can cause internal gas pressure buildup, leading to swelling, cracking, or delamination of the part. [47]

Some part made from binder jet (BJT), material extrusion (MEX) or fused filament fabrication (FFF) using metal or ceramic need to remove the binder and the main method is thermal debinding. The goal is to remove the organic binder or polymeric additives used to shape and hold the powder particles together during printing but still maintaining the structural integrity of the porous “brown part” before sintering. This is done at a controlled temperature, in an inert atmosphere (often made of argon or nitrogen) to minimize oxidation and other unwanted reactions. [?]

For example Dehghani et al. did the debinding in two step for stainless steel. First, a low-temperature phase (200–400°C) to evaporate volatile solvents and waxes, and then a higher-temperature phase (400–600°C) to thermally decompose polymeric binders such as polyvinyl butyral (PVB) or polyethylene glycol (PEG). After the binder is removed, the structure retains 60–65% of its theoretical density and exhibits sufficient strength for sintering at 1300–1360°C. The heating rate need to be optimize as well as the duration and the atmosphere to minimise internal cracking and warping but still ensuring homogene debinding throughout the component thickness as shown by Zissel. Lecis et al. demonstrated that, for binder-jetted 17-4 PH stainless steel, if an optimized thermal debinding cycle (2°C

$min^{-1}$  up to 600°C in nitrogen, 4h hold) followed by sintering at 1360°C is done, the relative density will be superior to 97% and the tensile strength increase to approximately 820 MPa, and this is comparable to wrought steel. Similarly German, R. M. shows that for tungsten and alumina alloy, thermal debinding combined with catalytic or solvent debinding steps are preventing defect formation during sintering. [48]

The driving force of thermal debinding is the reduction of the system's free energy through the removal of high-energy organic surfaces, enabling particle rearrangement and densification. The process kinetics can be described by Fickian diffusion of the binder vapor through the evolving pore network, often modeled by the Washburn equation. Furthermore, the debinding atmosphere significantly influences the chemical composition of the part: hydrogen atmospheres enhance carbon removal in steels, while vacuum or nitrogen minimize oxidation for reactive alloys such as titanium. [47]

## 4 Chemical Treatments

Chemical treatments are another important subset of post processing done to additively manufactured parts. The aim is to improve the properties of the components with the main advantage being the ability to also process surfaces that are hard to reach with mechanical methods discussed in section 2. The relative affordability and accessibility of the methods also makes it treatments that are frequently used [23]. The main treatments will be discussed in this section.

### 4.1 Chemical Polishing

Chemical polishing or sometimes referred as chemical etching or chemical bath finishing is one of the main chemical treatments done on AM parts. It is a process that is used for both metal and polymer parts. The part is immersed inside a chemical solution and is kept at a certain temperature for a certain amount of time. The content of the chemical solution, the temperature and the duration is optimized for different materials. Consequently, the roughness of the surface is decreased however it comes with a tradeoff of geometrical deviation [5, 49]. In the work done by Tyagi et al. chemical polishing was applied to SS316 using DS-9-314 solution comprising of a mixture of  $H_3PO_4$ ,  $HCl$  and  $HNO_3$ . The samples were kept between 30 to 90 minutes at  $75^\circ C$ . Using the optimized procedure, roughness ( $S_a$ ) was seen to decrease from 13.88 to 5.22 [50]. In another study internal cavity of an inconel samples roughness was reduced 23% however a reduction in thickness of  $50 \mu m$  was reported [51].

A research has been done to better the surface finish of ABS parts produced by FDM. A solution consisting of 90% Acetone and 10% water was used to keep the part for 300 seconds. The roughness ( $S_a$ ) was lowered down to  $1.88 \mu m$  with slight decrease in tensile strength and a slight increase in flexural strength was reported [52]. It is common to observe acetone being used for this purpose due to its affordability, low toxicity and high diffusion [53] which is why chemical polishing done with acetone on polymeric parts is sometimes referred as acetone dipping [23].

### 4.2 Vapour smoothing

Vapour smoothing is a process that is commonly applied to polymeric components. Instead of submerging the parts inside a solution as in the case of chemical polishing, the solution is vaporized and interacts with the surface of the component. As a result, a semi-solid slurry is formed where due to the surface tension gradients a reflow of the surface occurs filling the valleys decreasing surface roughness [54]. The illustration of the set up is as illustrated in figure 21. Study conducted by Chohan et al. studies vapour smoothing done on ABS parts manufactured with FDM for biomedical applications. They have reduced the surface roughness by 93% to achieve  $0.21 \mu m$  [55] which highlights the significance of this technique in terms of property improvement.

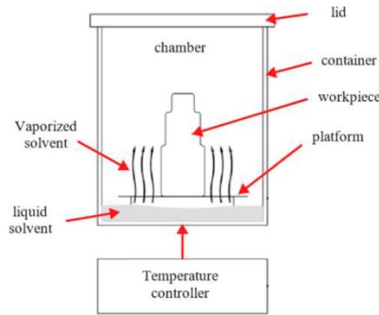


Figure 21: Vapour Smoothing [5].

### 4.3 Coating

Coating is a post-process that is often utilized with many methods to achieve certain properties of the surface. It is also used after an AM process to tackle mostly the roughness of the surface. There are many methods to coat a substrate, ranging from dip coating, spray coating to manual brushing or spraying. In all of these methods the valleys as well as the peaks are filled with the coat material to achieve a smooth surface. One disadvantage being the deviations of geometry from the CAD file. Another is the adhesion of the coated layer to the surface. Therefore, care must be given in process parameters to be applied. Zhu and his colleagues in their study, dip coated parts with different parameters [56]. In figure 22, the respective quality of the coatings are imaged. With this figure, the importance to have optimized process parameters are emphasized and the decrease of roughness is visualized.

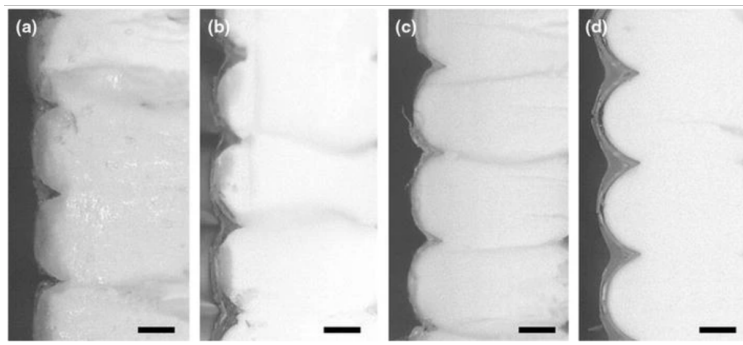


Figure 22: Dip coating done under different process parameters shown through a-d [56].

### 4.4 Electroplating

Post-processing can also be applied not only to mitigate the defects that might have arisen during the manufacturing process but also to enhance the properties of the part. Electroplating is one such method where the aim is to deposit a thin layer of metallic part on top of the part. In this sense it is similar to coating mentioned in the above subsection however electrical and chemical principles are applied together in this process. The process illustration is given in figure 23. The sample and the desired plating material is used to create a cell where the part acts as the cathode and the plating material as the anode.

The electrolyte allows for the metallic ions form at the anode to reduce in the cathode to eventually form the metallic thin layer covering the surface.

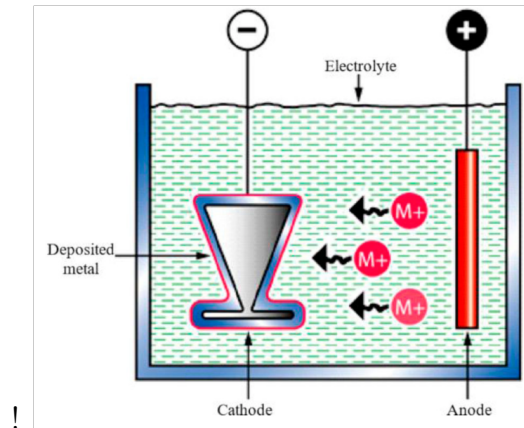


Figure 23: Electroplating illustration [5].

This method has been applied to impart corrosion resistance, hardness, impact and tensile strength on the manufactured parts [5]. Furthermore, roughness can also be decreased coming from the same principles as coating. This process is also applicable to polymeric materials where conductivity can be imparted as well as improvement in roughness and strength.

## 4.5 Electrochemical finishing

Electrochemical finishing also utilizes both chemical and electrical principles, with the metallic workpiece serving as the anode. Therefore, instead of depositing to the workpiece, material is subtracted allowing to essentially polish the surface. The setup of the cell is given in figure 24 (a). The advantage of this method consists of the capability to control precisely the process conditions due to them relying on well studied electrochemical principles. In figure 24, the comparison of as built part and after electrochemical finishing is shown. It is possible to observe that the surface roughness has visibly decreased including the internal cavities.

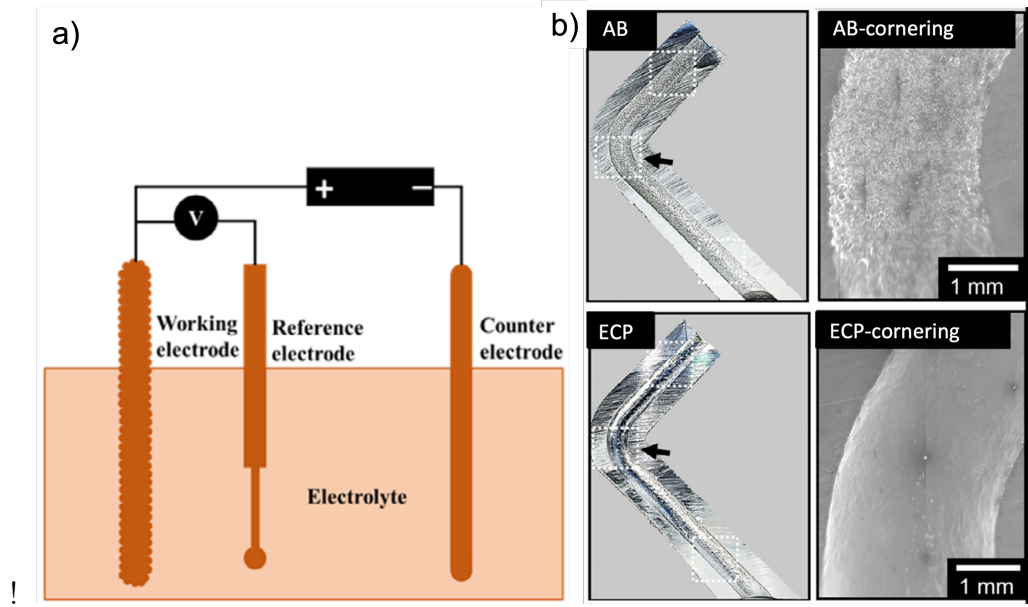


Figure 24: a) The schema of a Electrochemical finishing cell and b) comparison of as built and electrochemically finished sample [49].

## 5 Conclusion

Additive manufacturing allows the production of complex geometries in parts. However, there are still challenges such as surface roughness, residual stresses, porosity, anisotropic microstructures, and dimensional inaccuracies after processing. Post-processing treatments are therefore needed to ensure that parts keep their mechanical, thermal, and surface properties required for their applications.

In this report, the main categories of post-processing: mechanical, thermal, and chemical were analyzed to show how each impact the quality of AM parts. Mechanical treatments, such as abrasive flow machining, ultrasonic surface modification, and shot peening, are improving and refining surface topography, decreasing compressive residual stresses, and improving fatigue strength. The component's lifetime are longer and there is fewer crack initiation sites caused by staircase effects or partially melted powder particles.

Thermal treatments are used mainly for microstructural optimization. Processes such as hot isostatic pressing (HIP), sintering, and infiltration directly reduce porosity and so increase densities up to 99% in metallic systems. Traditional heat treatments such as annealing, stress-relief, solution treatment, and aging enable stress relaxation, phase homogenization, and precipitation hardening, allows to refine mechanical properties and combinations of strength and ductility can be optimized. These methods are enhancing fatigue resistance and corrosion stability. Furthermore, thermal debinding is used as a transitional stage that ensures the removal of polymeric binders and prevents deformation or cracking during sintering.

Chemical post-processing methods improve surface defects inaccessible to mechanical tools. Techniques such as chemical polishing, vapor smoothing, electroplating, and electrochemical finishing allow a controlled removal or deposition at the microscale, and it gives smoother surfaces and improved corrosion resistance. These methods are particularly useful for complex geometries with internal channels where mechanical finishing is impractical.

Overall, the integration of several post-processing techniques often combining mechanical, thermal, and chemical treatment maximizes surface integrity and bulk mechanical performance. The studies reviewed demonstrate that selecting appropriate treatments specific to the material system and application is essential to have good performance. The reached properties thanks to post-processing can be as high as traditionally machined parts. Hence, additive manufacturing is not only for prototyping.

## 6 Distribution of Work

**Koray Kelam:** Author of the Abrasive Methods (Section 2.1), Subtractive Machining Methods (Section 2.2), and Mechanical Deformation-Based Methods (Section 2.3).

**Sude Yaşar:** Author of the Mass Finishing (Section 2.4) and the Fatigue Life Enhancement Processes (Section 2.5).

**Doruk Sinayuc:** Author of the Introduction (Section 1) and the Chemical Treatments (Section 4).

**Laura Cheng:** Author of the Thermal Treatments (Section 3) and the Conclusion (Section 5).

## References

- [1] Mark Armstrong, Hamid Mehrabi, and Nida Naveed. An overview of modern metal additive manufacturing technology. *Journal of Manufacturing Processes*, 84:1001–1029, 12 2022.
- [2] Ian Gibson, David Rosen, Brent Stucker, and Mahyar Khorasani. *Additive Manufacturing Technologies*. Springer, 3 edition, 2021.
- [3] Osama Abdulhameed, Abdulrahman Al-Ahmari, Wadea Ameen, and Syed Hammad Mian. Additive manufacturing: Challenges, trends, and applications. *Advances in Mechanical Engineering*, 11, 2 2019.
- [4] Niloofar Sanaei, Ali Fatemi, and Nam Phan. Defect characteristics and analysis of their variability in metal l-pbf additive manufacturing. *Materials and Design*, 182, 11 2019.
- [5] F. Tamburrino, S. Barone, A. Paoli, and A. V. Rationale. Post-processing treatments to enhance additively manufactured polymeric parts: a review. *Virtual and Physical Prototyping*, 16:221–254, 2021.
- [6] Petronilo Martin-Iglesias, Maarten van der Vorst, Johannes Gumpinger, and Tommaso Ghidini. Esa’s recent developments in the field of 3d printed rf/microwave hardware. In *11th European Conference on Antennas and Propagation (EUCAP)*. IEEE, 2017.
- [7] Hamaid Mahmood Khan, Yusuf Karabulut, Ozhan Kitay, Yusuf Kaynak, and I. S. Jawahir. Influence of the post-processing operations on surface integrity of metal components produced by laser powder bed fusion additive manufacturing: a review. *Machining Science and Technology*, 25:118–176, 2020.
- [8] Vivek Tiwary, P. Arunkumar, Anand Deshpande, and Nikhil R. Surface enhancement of FDM patterns to be used in rapid investment casting for making medical implants. *Rapid Prototyping Journal*, 25, 06 2019.
- [9] Ashif Sikandar Iquebal, Skander El Amri, Sanjay Shrestha, Zimo Wang, Guha P. Manogharan, and Satish Bukkapatnam. Longitudinal Milling and Fine Abrasive Finishing Operations to Improve Surface Integrity of Metal AM Components. *Procedia Manufacturing*, 10:990–996, 2017. 45th SME North American Manufacturing Research Conference (NAMRC 45), LA, USA.
- [10] Ashif Sikandar Iquebal, Dinakar Sagapuram, and Satish Bukkapatnam. Surface plastic flow in polishing of rough surfaces. *arXiv preprint arXiv:1610.09719*, October 2016.
- [11] Y. Peng et al. Study on improvement of surface roughness and induced residual stress for additively manufactured metal parts by abrasive flow machining. *Procedia CIRP*, 71:386–389, 2018. 4th CIRP Conference on Surface Integrity (CSI 2018).
- [12] Daniyar Syrlybayev, Aidana Seisekulova, Didier Talamona, and Asma Perveen. The Post-Processing of Additive Manufactured Polymeric and Metallic Parts. *Journal of Manufacturing and Materials Processing*, 6(5), 2022.

- [13] Kah Fai Leong, Chee Kai Chua, Gim Siong Chua, and Chee Hock Tan. Abrasive jet deburring of jewellery models built by stereolithography apparatus (sla). *Journal of Materials Processing Technology*, 83(1):36–47, 1998.
- [14] Ruslan Melentiev and Fengzhou Fang. Recent Advances and Challenges of Abrasive Jet Machining. *CIRP Journal of Manufacturing Science and Technology*, 22:1–20, 2018.
- [15] Pulak M. Pandey, N. Venkata Reddy, and Sanjay G. Dhande. Improvement of Surface Finish by Staircase Machining in Fused Deposition Modeling. *Journal of Materials Processing Technology*, 132(1):323–331, 2003.
- [16] Alberto Boschetto, Luana Bottini, and Francesco Veniali. Finishing of Fused Deposition Modeling Parts by CNC Machining. *Robotics and Computer-Integrated Manufacturing*, 41:92–101, 2016.
- [17] Chi Ma, Yalin Dong, and Chang Ye. Improving surface finish of 3D-Printed Metals by Ultrasonic Nanocrystal Surface Modification. *Procedia CIRP*, 45:319–322, 2016. 3rd CIRP Conference on Surface Integrity.
- [18] Ming Tan, Shang-Shen Yeo, X. Tan, and Shu Beng Tor. Surface modification of additive manufactured components by ultrasonic cavitation abrasive finishing. *Wear*, 378-379:90–95, 2017.
- [19] David A. Davidson. Mass finishing processes. *Metal Finishing*, 99:110–124, 2001.
- [20] Mikdam Jamal and Michael N. Morgan. Design process control for improved surface finish of metal additive manufactured parts of complex build geometry. *Inventions*, 2(4):36, 2017.
- [21] Foxian Fan, Kazi Shahed, and Guha Manogharan. Cost analysis of mass finishing additively manufactured ti6al4v parts. In *Proc.*, May 2023.
- [22] Foxian Fan, Sagar Jalui, Kazi Shahed, Brigid Mullany, and Guha Manogharan. Mass finishing for additive manufacturing: Tribological analysis, surface topology, image processing, predictive model, and processing recommendations. *Tribology International*, 204:110486, 2025.
- [23] Zafar Alam, Faiz Iqbal, and Dilshad Ahmad Khan. *Post-Processing Techniques for Additive Manufacturing*. CRC Press, Boca Raton, FL, 2024.
- [24] William Nebiolo. Increasing vibratory efficiency by optimizing the choice of media shape relative to part geometry. *Products Finishing*, 75(11):20, 2011.
- [25] Mahyar Khorasani, Ian Gibson, AmirHossein Ghasemi, Milan Brandt, and Martin Leary. On the role of wet abrasive centrifugal barrel finishing on surface enhancement and material removal rate of lpbf stainless steel 316l. *Journal of Manufacturing Processes*, 59:523–534, 2020.

- [26] Eckart Uhlmann and Alexander Eulitz. Influence of ceramic media composition on material removal in vibratory finishing. *Procedia CIRP*, 72:1445–1450, 2018.
- [27] S. Wang, R. S. Timsit, and J. K. Spelt. Experimental investigation of vibratory finishing of aluminum. *Wear*, 243(1):147–156, 2000.
- [28] Mohammad Reza Baghbanan, Akihiro Yabuki, Roland S. Timsit, and Jan K. Spelt. Tribological behavior of aluminum alloys in a vibratory finishing process. *Wear*, 255(7):1369–1379, 2003.
- [29] A. Yabuki, M. R. Baghbanan, and J. K. Spelt. Contact forces and mechanisms in a vibratory finisher. *Wear*, 252(7):635–643, 2002.
- [30] R. Mediratta, K. Ahluwalia, and S. H. Yeo. State-of-the-art on vibratory finishing in the aviation industry: an industrial and academic perspective. *International Journal of Advanced Manufacturing Technology*, 85(1-4):415–429, 2016.
- [31] Kai Liang Tan, Eng Tiong Neoh, Joseph John Lifton, Wei Shin Cheng, and Sho Itoh. Internal measurement of media sliding velocity in a stream finishing bowl. *International Journal of Advanced Manufacturing Technology*, 120(7-8):4681–4691, 2022.
- [32] Frederik Zanger, Andreas Kacaras, Patrick Neuenfeldt, and Volker Schulze. Optimization of the stream finishing process for mechanical surface treatment by numerical and experimental process analysis. *CIRP Annals*, 68(1):373–376, 2019.
- [33] Inovatec Machinery. Centrifugal disc finishing machines, 2025. Accessed: Nov. 5, 2025.
- [34] C. Ye, C. Zhang, J. Zhao, and Y. Dong. Effects of post-processing on the surface finish, porosity, residual stresses, and fatigue performance of additive manufactured metals: A review. *Journal of Materials Engineering and Performance*, 30(9):6407–6425, 2021.
- [35] A. Chueca de Bruijn, G. Gómez-Gras, and M. A. Pérez. On the effect upon the surface finish and mechanical performance of ball burnishing process on fused filament fabricated parts. *Additive Manufacturing*, 46:102133, 2021.
- [36] I. F. Ituarte, M. Salmi, S. Papula, J. Huuki, B. Hemming, E. Coatanea, S. Nurmi, and I. Virkkunen. Surface modification of additively manufactured 18% nickel maraging steel by ultrasonic vibration-assisted ball burnishing. *Journal of Manufacturing Science and Engineering*, 142(7), 2020.
- [37] Lloyd Hackel, Jon R. Rankin, Alexander Rubenchik, Wayne E. King, and Manyalibo Matthews. Laser peening: A tool for additive manufacturing post-processing. *Additive Manufacturing*, 24:67–75, 2018.
- [38] Jun Ge, Selvum Pillay, and Haibin Ning. Post-process treatments for additive-manufactured metallic structures: A comprehensive review. *Journal of Materials Engineering and Performance*, 32(16):7073–7122, August 2023.

- [39] Xing Peng, Lingbao Kong, Jerry Ying Hsi Fuh, and Hao Wang. A review of post-processing technologies in additive manufacturing. *Journal of Manufacturing and Materials Processing*, 5(2):38, 2021.
- [40] Matteo Benedetti, Elisa Torresani, Matteo Leoni, Vittorio Fontanari, Marco Bandini, Carla Pederzoli, and Chiara Potrich. The effect of post-sintering treatments on the fatigue and biological behavior of ti-6al-4v eli parts made by selective laser melting. *Journal of the Mechanical Behavior of Biomedical Materials*, 71:295–306, 2017.
- [41] Randall M. German. *Sintering: From Empirical Observations to Scientific Principles*. Elsevier, Oxford, UK, 2014.
- [42] Lindsey B. Bezek, Ryan P. Wilkerson, Jonah L. Chad, Theresa E. Quintana, Brian M. Patterson, Santosh Adhikari, and Kwan-Soo Lee. Evolution of debinding and sintering of a silica-based ceramic using vat photopolymerization additive manufacturing. *Additive Manufacturing*, 105:104795, 2025.
- [43] Nicola Lecis, Emanuele Gariboldi, Paolo Bassani, and Maurizio Vedani. Effects of process parameters, debinding and sintering on the densification of binder-jetted metal parts. *Journal of Materials Processing Technology*, 295:117167, 2021.
- [44] David Impens and R. J. Urbanic. Assessing the impact of post-processing variables on tensile and compression characteristics for 3d printed components. In *IFAC-PapersOnLine*, volume 28, pages 652–657, 5 2015.
- [45] Alin Diniță, Adrian Neacșa, Alexandra Ileana Portoacă, Maria Tănase, Costin Nicolae Ilinca, and Ibrahim Naim Ramadan. Additive manufacturing post-processing treatments: A review with emphasis on mechanical characteristics. *Materials*, 16(13):4610, 2023.
- [46] Vijayakumar Praveen Kumar and Alfred Vinoth Jebaraj. Attainment of favorable microstructure for residual stress reduction through high-temperature heat treatment on additive manufactured inconel 718 alloy. *The International Journal of Advanced Manufacturing Technology*, 121(7–8):4455–4472, 2022.
- [47] Katharina Zissel. Influence of the processing atmosphere on binder jetting of 17-4 ph stainless steel. Master’s thesis, Chalmers University of Technology, Gothenburg, Sweden, 2024.
- [48] M. B. Dehghani, M. K. Thompson, and T. Wohlers. Thermal debinding and sintering of binder-jet printed 316l stainless steel parts: Process optimization and defect prevention. *Additive Manufacturing*, 40:101942, 2021.
- [49] Shamim Pourrahimi and Lucas A. Hof. On the post-processing of complex additive manufactured metallic parts: A review. *Advanced Engineering Materials*, 26, 5 2024.

- [50] Pawan Tyagi, Tobias Goulet, Christopher Riso, Robert Stephenson, Nitt Chuenprateep, Justin Schlitzer, Cordell Benton, and Francisco Garcia-Moreno. Reducing the roughness of internal surface of an additive manufacturing produced 316 steel component by chempolishing and electropolishing. *Additive Manufacturing*, 25:32–38, 1 2019.
- [51] Neda Mohammadian, Sylvain Turenne, and Vladimir Brailovski. Surface finish control of additively-manufactured inconel 625 components using combined chemical-abrasive flow polishing. *Journal of Materials Processing Technology*, 252:728–738, 2 2018.
- [52] L. M. Galantucci, F. Lavecchia, and G. Percoco. Quantitative analysis of a chemical treatment to reduce roughness of parts fabricated using fused deposition modeling. *CIRP Annals - Manufacturing Technology*, 59:247–250, 2010.
- [53] L. M. Galantucci, F. Lavecchia, and G. Percoco. Experimental study aiming to enhance the surface finish of fused deposition modeled parts. *CIRP Annals - Manufacturing Technology*, 58:189–192, 2009.
- [54] S.M. Basha, M.M. Basha, N. Venkaiah, and Mamilla Ravi Sankar. State of art on vapour smoothing of fused deposition modelling components. *Applied Mechanics and Materials*, 903:57–63, 4 2021.
- [55] Jasgurpreet Singh Chohan, Rupinder Singh, and Kamaljit Singh Boparai. Parametric optimization of fused deposition modeling and vapour smoothing processes for surface finishing of biomedical implant replicas. *Measurement: Journal of the International Measurement Confederation*, 94:602–613, 12 2016.
- [56] Jiayi Zhu, Julia L. Chen, Robert K. Lade, Wieslaw J. Suszynski, and Lorraine F. Francis. Water-based coatings for 3d printed parts. *Journal of Coatings Technology and Research*, 12:889–897, 9 2015.